Out-going Muon Flux from Neutralino Annihilation in the Sun and the Earth in Supergravity Unification

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Abstract

Predictions for the out-going muon fluxes from the annihilation of neutralinos in the center of the Sun and the Earth in supergravity unification are given. Effects of uncertainties of the input data are analysed. It is shown that the out-going muon flux measurements from the Sun and the Earth are complementary, with the Earth providing a larger flux for low values of fine tuning and the Sun providing a larger flux for high values of fine tuning, and that only a combination of the two can compete favorably with the direct detection measurements. The predictions are compared with the recent limits from BAIKAL NT-96, MACRO, and BAKSAN.

Recently analyses of the data from several neutrino telescopes (BAIKAL NT-96[1],MACRO[2], BAKSAN[3]) have produced bench mark limits on the out-going muon fluxes from the annihilation of dark matter wimps in the centers of the Sun and the Earth[4−6]. In this Letter we give predictions for these out-going muon fluxes in supergravity grand unification[7,8] taking into account the uncertainties in the local wimp density as well as the uncertainties in the rms wimp velocity and we compare these predictions with the recent experimental limits[1−3]. We study the relative merit of using the Sun vs the Earth for the detection of dark matter as the SUSY spectrum gets progressively heavier and the fine tuning parameter of the radiative electro-weak symmetry breaking gets progressively larger. We also make a similar comparison of the direct vs the indirect detection of neutralino dark matter and show that only a combination of the out-going flux measurements from the Sun

and the Earth can compete effectively with the direct detection of neutralino dark matter in mapping the parameter space of minimal supergravity.

Supergravity unified models are extensions of the Standard Model, consistent with all current data, and under the constraint of R partiy invariance lead to the existence of a cosmologically stable neutralino $\tilde{\chi}_1^0$ which can act as a candidate for cold dark matter. In these models the breaking of supersymmetry takes place in the hidden sector and the breaking is communicated via gravitational interactions to the visible sector where the breaking of supersymmetry can be parametrized by the following set for the minimal case (mSUGRA)[8]: the universal scalar mass (m_0) at the GUT scale, the universal gaugino mass ($m_{1/2}$) at the GUT scale, the universal trilinear coupling A_0 at the GUT scale, $tan\beta =< H_2 > / < H_1 >$, where $< H_2 >$ gives mass to the up quarks and $< H_1 >$ gives mass to the down quarks and the leptons, and sign(μ) where $\mu H_1 H_2$ is the Higgs mixing term in the superpotential. Detailed relic density analyses show that supergravity models can produce a wimp relic density consistent with a range of current cosmological models. We shall assume this relic density to lie in the range $0.05 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.3$, where $\Omega_{\tilde{\chi}_1^0} = \rho_{\tilde{\chi}_1^0}/\rho_c$, with $\rho_{\tilde{\chi}_1^0}$ the average density of neutralinos in the universe and $\rho_c = 3H^2/8\pi G_N$ the critical matter density, where G_N is the Newtonian constant and h is the Hubble parameter in units of $100 km sec^{-1} Mpc^{-1}$.

The basic elements of the analysis of the physics of out-going muons are the following: The Milky Way neutralinos are trapped by scattering and gravitational pull by the Earth and the Sun and accumulate in their cores where they eventually annihilate. Some of the final annihilation remnants contain neutrinos which propagate and undergo charge current interactions in the rock surrounding the detector and produce out-going muons which are detected. The basic theory of the various elements of the analysis are fairly well laid out and we follow the standard literature here[4,5]. However, we point out some basic features where specific elements of the SUGRA models enter. The flux of the out-going muons is given by $\Phi_\mu = \Gamma_A f$, where Γ_A is the rate of $\tilde{\chi}_1^0 - \tilde{\chi}_1^0$ annihilation in the center of the Earth or the Sun and f is the product of remaining factors[4–6]. A significant portion of the SUSY dependence in contained in Γ_A which is given analytically by[9]

$$\Gamma_A = \frac{C}{2} tanh^2(t/\tau) \tag{1}$$

Here C is the capture rate of the neutralinos which depends on the wimp relic density and on the wimp-nucleus cross section, t is the age of the Earth or the Sun and $\tau = (CC_A)^{-1/2}$ where C_A depends on the wimp annihilation cross-section. In the limit $t >> \tau$, one finds $\Gamma_A \sim C/2$, i.e., an equilibrium is reached between annihilation and capture. The condition of equilibrium depends on the particulars of the SUSY parameter space. For the case of the Sun one finds that the equilibrium condition is realized over essentially all of the parameter space of the model while for the case of the Earth this condition is highly model dependent.

The predictions of the out-going muon fluxes in supergravity unifed models will be constrained by several factors. In addition to the radiative electro-weak symmetry breaking[8] and the relic density constraints we impose the constraint from the flavor changing neutral current process $b \rightarrow s + \gamma$. This process is known to constrain dark matter analyses severely by eliminating large segments of the mSUGRA parameter space via the relic density constraint[10]. The parameter space of mSUGRA will be further constrained by the naturalness criterion which we take to imply $m_0 \leq 1$ TeV, $m_{\tilde{g}} \leq 1$ TeV, $tan\beta \leq 25$, and $-7 \leq (A_t/m_0) \leq 7$, where A_t is the value of A_0 at the electro-weak scale for the top quark channel. In the analysis of the relic density we use the accurate method which includes the correct thermal averaging over the Breit-Wigner poles in the neutralino s channel annihilation[11].

In the analysis below we study the dependence of our predictions for the out-going muon fluxes from the Earth and the Sun including the uncertainties of the neutralino relic density in the Milky Way. Current estimates show that the local wimp density can vary in the range[12] $(0.2 - 0.7) GeV cm^{-3}$. We parametrize this variation by $\xi = \rho_{\tilde{\chi}_1^0}/\rho_0$ which for $\rho_0 = 0.3 GeV cm^{-3}$ lies in the range $0.7 \leq \xi \leq 2.3$. Further, we study the dependence of the out-going muon fluxes on the uncertainties in the wimp velocity[13] the details of which are given below. There could also be effects on the out-going muon fluxes due to rotation of the galaxy[14]. However, such effects may be small (e.g. an analysis of these effect on the direct

detection rates of dark matter was found to be only $\sim 10\%$). A brief discussion of the effects on the prediction of the muon fluxes under the constraint of the annual modulation signal claimed by the DAMA Collaboration[15] is also given. Finally, we give an analysis of the out-going muon flux from the Sun and the Earth as a function of the fine tuning parameter and discuss the relative merits of the direct vs the indirect detection. In the analysis below we neglect the ν oscillation effects. These effects could modify the detection rates from $10\% - 50\%$ but are highly model dependent on the nature of the assumed ν oscillation[16]. Inclusion of these effects would not change the conclusions of this work.

We discuss now the results of our analysis. In Fig.(1a) a plot of the maximum out-going muon flux for the case of the Earth is given as a function of $m_{\tilde{\chi}_1^0}$ for three ξ values: $\xi = 0.7$, $\xi = 1$ and $\xi = 2.3$. One finds that the maximum out-going muon flux is generally peaked for $m_{\tilde{\chi}_1^0}$ below 60 GeV after which it shows a fall off with increasing $m_{\tilde{\chi}_1^0}$. Interestingly one finds that the MACRO limits are already stringent enough to put constraints on mSUGRA in this case although the part of the parameter space so constrained is rather small. In Fig.(1b) a similar plot is given for the case of the out-going muon flux from the Sun. However, here the MACRO limits do not put any constraint on mSUGRA. In fact, the experimental sensitivity will have to increase by a factor of 10 or more before mSUGRA can be constrained by the Sun flux. A comparison of Fig.(1a) and Fig.(1b) shows that for relatively low values of $m_{\tilde{\chi}_1^0}$ the Earth provides a better source for wimp detection relative to the Sun. We shall return to a more detailed comparison of the goodness of the Earth vs the Sun for wimp detection in the discussion of Fig.3.

The analysis of Figs.(1a) and Fig.(1b) was based on a Maxwellian velocity distribution of the wimps with an rms wimp velocity of $v = 270\ km/s$. However, there is the possibility of a significant uncertainty in the rms wimp velocity with estimates of the uncertainty ranging from ± 24 km/s to ± 70 km/s[13]. For illustrative purposes we study the effects for the range $v = 270 \pm 50\ km/s$. The results are shown in Fig.(2a) for the maximum out-going muon flux for the Earth and in Fig.(2b) for the maximum out-going muon flux for the Sun. Here we find that the ± 50 km/s variation of the rms wimp velocity can generate significant variations

in the out-going muon fluxes. Next we discuss the effect on our analysis of including the constraints that will allow the annual modulation signal in the direct detection of wimps claimed by the DAMA Collaboration[15]. The constraint that the supergravity unified models generate $\tilde{\chi}_1^0$-proton cross-sections compatible with the annual modulation signal observed by DAMA has been analysed elsewhere[17,18] and the reduced set of mSUGRA configurations compatible with the claimed DAMA signal have been identified[17,18]. An analysis including the DAMA constraint shows that the peak values of the maximum out-going muon fluxes for the Earth and the Sun are not significantly affected. Thus at least in the peak region the MACRO limits for the out-going muon flux for the Earth put a further constraint on the reduced set of configurations allowed by the DAMA cut[17,18].

In Fig.(3a) we study the mean out-going muon flux gotten by averaging over the allowed parameter space for fixed fine tuning Φ as a function of $\sqrt{\Phi}$. Roughly speaking the fine tuning parameter measures how heavy the SUSY spectrum is and we use here the criterion given in Ref.[19] which defines $\Phi=\frac{1}{4}+\frac{\mu^2}{M_Z^2}$. Fig.(3a) shows that the mean out-going muon flux decreases sharply with $\sqrt{\Phi}$. Remarkably one finds that the Earth flux falls by many more decades than the Sun flux over the allowed range of $\sqrt{\Phi}$. Thus for low values of $\sqrt{\Phi}$, i.e., $\sqrt{\Phi} \leq 2.5$ (which imply a relatively light SUSY spectrum) the Earth flux would be more easily accessible to neutrino telescope searches, while an opposite situation holds for larger $\sqrt{\Phi}$ values, i.e., $\sqrt{\Phi} \geq 2.5$ (which imply a relatively heavy SUSY spectrum). This means that for a low SUSY mass spectrum, e.g., with values near the current experimental lower limits from accelerators, the prime source for the discovery of dark matter wimps for neutrino telescopes is the out-going muon flux from the Earth. However, as the lower limits on the SUSY masses at accelerators increase and approach their naturalness limits, the out-going muon flux from the Sun will become the prime source for the discovery of dark matter wimps for neutrino telescopes. Of course, as the SUSY spectrum becomes progressively heavier, one would need progressively larger sensitivities in neutrino telescopes to probe the parameter space remaining in supergravity models.

Finally we discuss the relative merits of the indirect vs the direct detection (For the

details of computation of direct detection rates see, e.g., Ref.[20]). In Fig.(3b) the maximum and the minimum out-going muon flux from the Sun and the Earth is plotted against the direct detection rate for Ge. The analysis shows that while the direct detection rate spans a wide range, i.e., roughly about 4 decades, this range is much smaller than the range of the out-going muon flux from the Earth. However, the range of the outgoing muon flux from the Sun is comparable to the range of the direct detection rate. The analysis implies that the direct detection will certainly be superior to measurements from neutrino telescopes using only the out-going muon flux from the Earth at least for relatively larger fine tunings (i.e., $\Phi > 2.5$, see Fig.(3a)). However, for relatively larger fine tunings the out-going muon flux measurements from the Sun will compete favorably with the direct detection measurements.

In summary our conclusion is that neutrino telescopes measuring the out-going muon flux only for the Earth or only for the Sun cannot compete with the direct dark matter searches in mapping the full parameter space of mSUGRA within the assumed naturalness limits. However, the out-going muon flux measurements from both the Earth and the Sun can be competitive with the direct dark matter searches provided the improvement in the sensitivities of the indirect and the direct detection measurements keep pace, i.e., the sensitivity of measurements improves by the same number of decades in each experiment. We have also investigated the effects of non-universalities of the soft SUSY breaking parameters at the GUT scale on the analysis presented here. Our conclusions here are very similar to the one's given above. The predictions of the muon fluxes given here and their dependence on fine tuning will have implications for other neutrino telescopes regarding their ability to search for supersymmetric dark matter, e.g., AMANDA[22] at the South Pole which is collecting data and possibly other future neutrino telescopes which are in the developmental stage.

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FIGURES

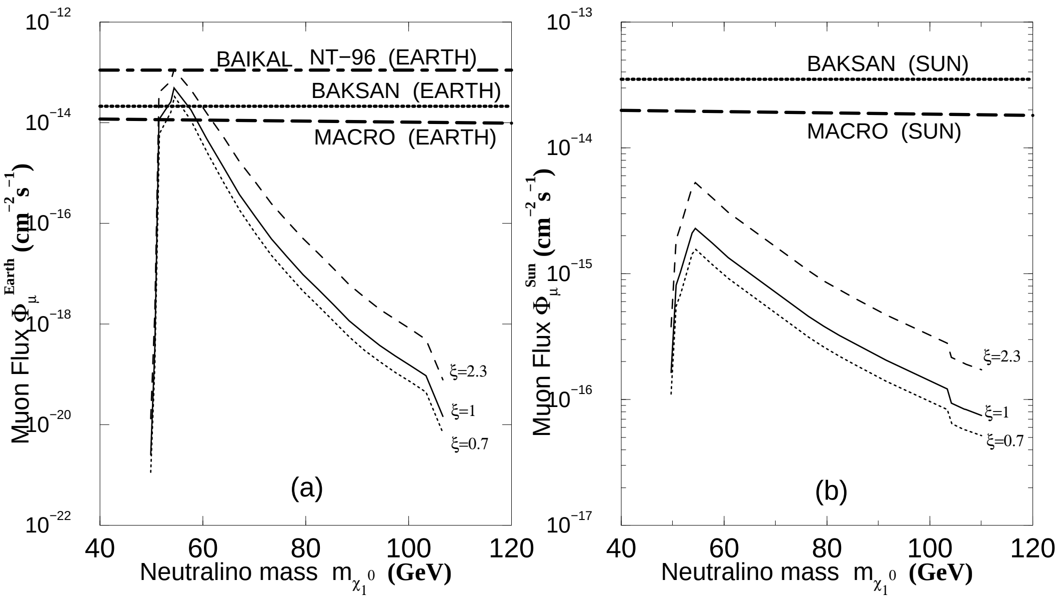

Fig. 1. (a): Plot of the maximum out-going muon flux for the Earth in mSUGRA as a function of the neutralino mass for three different values of the local wimp density corresponding to $\xi = 0.7, 1, 2.3$, and $\mu > 0$ (Our μ sign convention is as in Ref.[19]). The horizontal lines show limits from experiment; (b) Same as (a) except for the Sun.

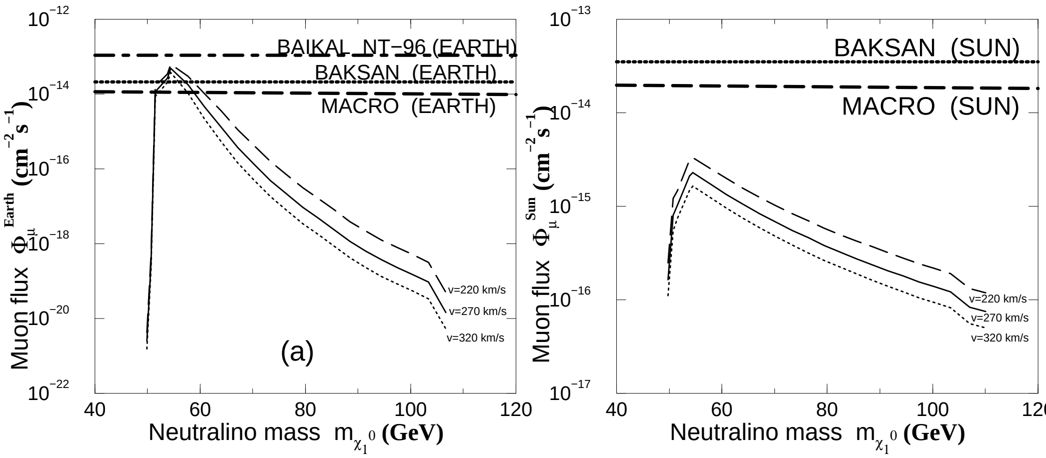

Fig. 2. Same as Fig.(1a) except that the analysis is for $\xi = 1$ and for three different rms wimp velocities in the halo, i.e., v=220 km/s, 270 km/s, and 320 km/s. (b) Same as (a) except for the Sun.

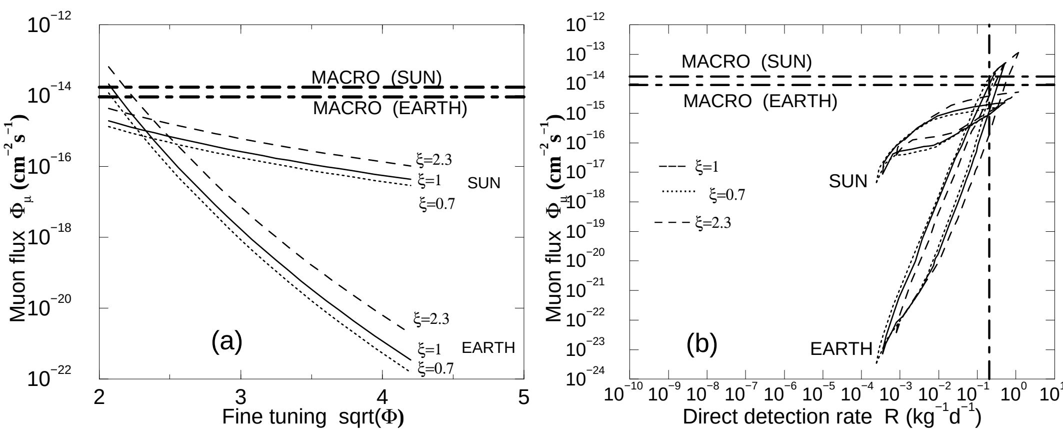

Fig. 3. (a): Plot of the mean out-going muon flux for the Sun and the Earth as a function of the fine tuning parameter $\sqrt{\Phi}$ for three values of ξ. The experimental limits from MACRO, which are currently the best limits, are shown by the horizontal lines; (b) Plot of the maximum and the minimum of the out-going muon flux for the Sun and for the Earth as a function of the direct detection rate for Ge. The verticle line is the upper limit from Ref.[20].

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